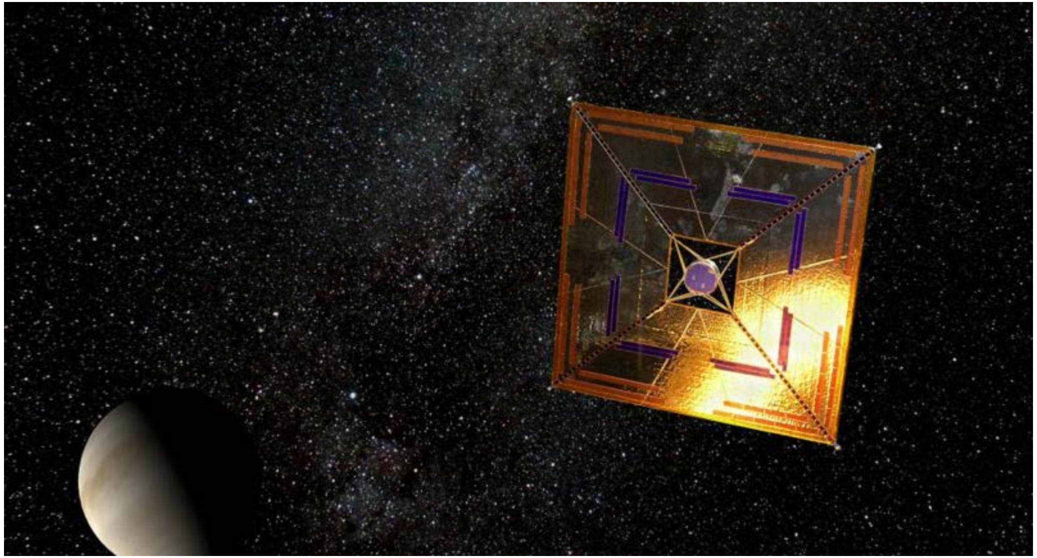
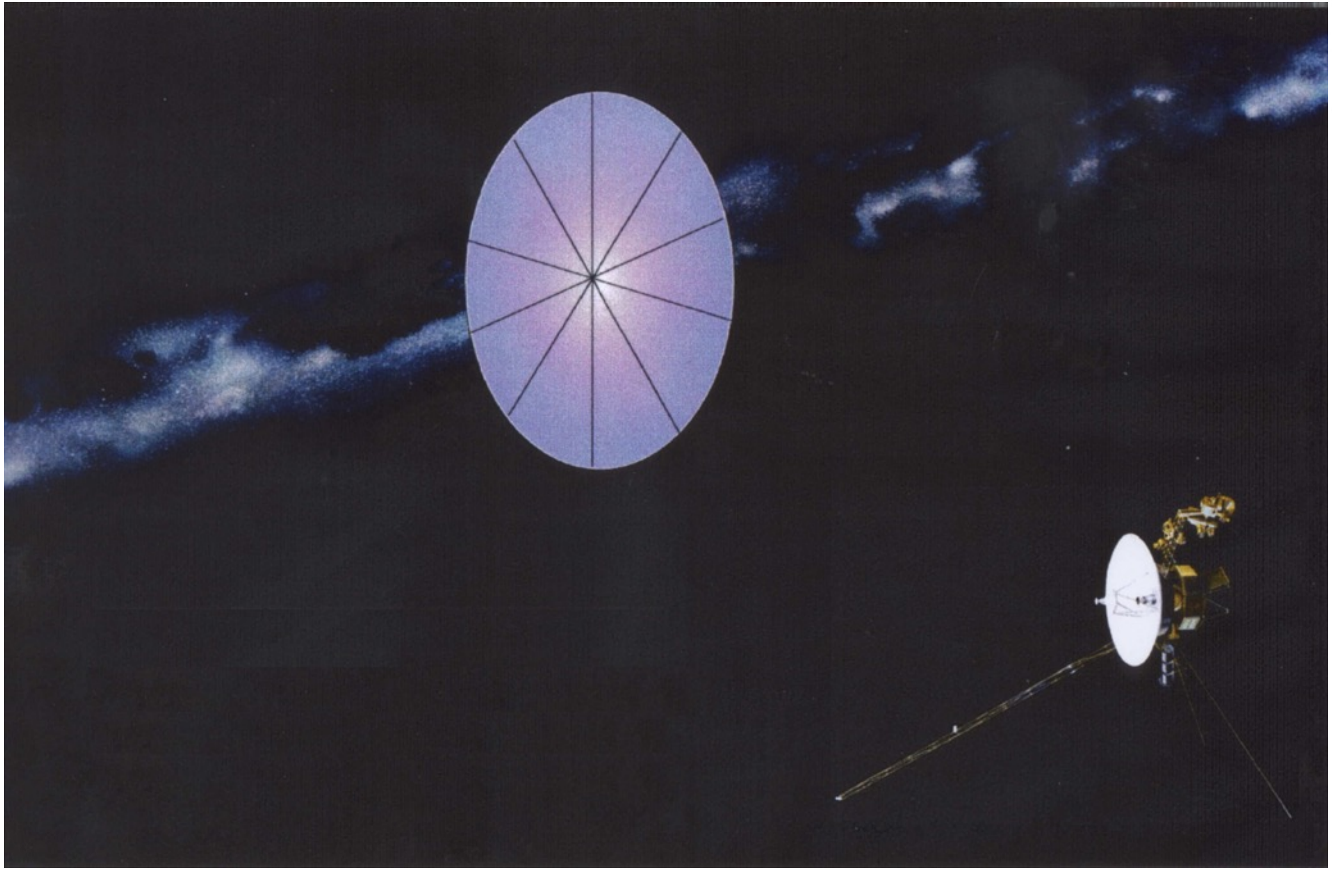


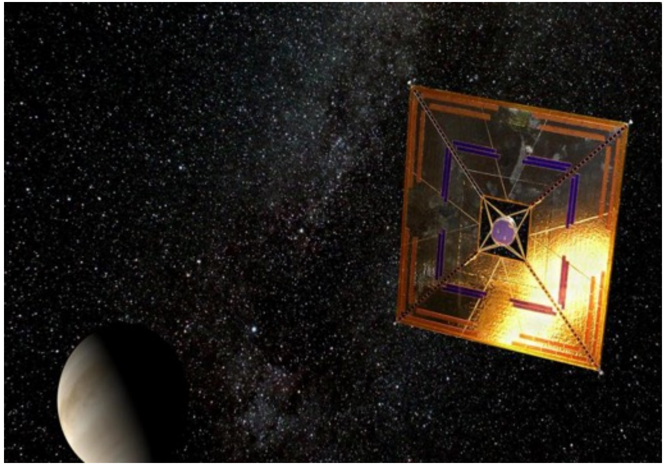
Power System for Miniature Interstellar Flyby Probe

Geoffrey A. Landis, NASA Glenn Research Center, Cleveland, Ohio, 44135

6th Interstellar Symposium, Wichita KS, Nov. 10-15 2019.



Artist's conception:
Laser-pushed sail passes Voyager 1 at 150 AU from the sun, 4½ days after launch



Proposed concept for an interstellar probe: ultra-lightweight laser-pushed lightsail flying past an exoplanet at 20% of the speed of light

Builds on interstellar sail concepts developed by many researchers over many decades, with particular focus on the work of Robert L. Forward and Philip Lubin

The problem

- Sail propelled missions to the nearest stars are now being proposed… but in order to be possible, interstellar probes must be extremely small: total mass measured in **grams** (compare to ~400 kg for New Horizons).
- What do you do when you get there? *Power* is needed for sensors and to communicate results.
- Power source for the interstellar micro-probe is a difficult problem: no existing power sources meet the requirements within the strict mass limits.

The solution

- Can we harvest power from the spacecraft's motion?
- Spacecraft is moving with respect to the target star's plasma environment (solar wind) and interplanetary magnetic field
- Can we use this to generate power?

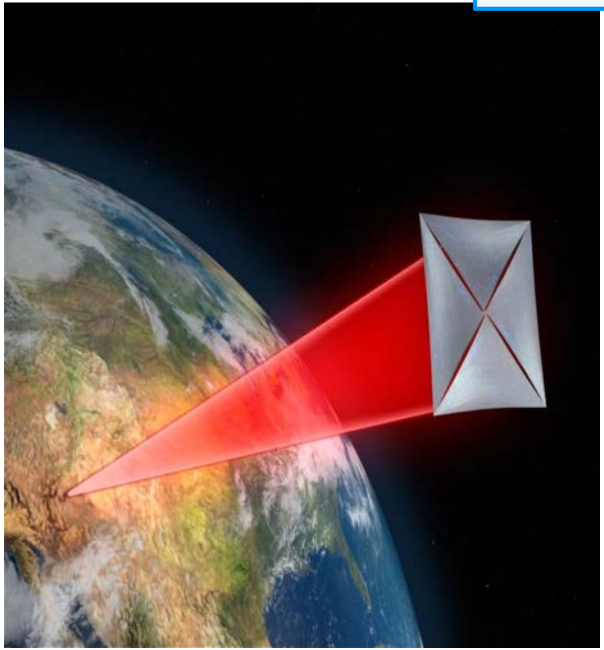
Power: a key technology

- For example, the Breakthrough Starshot project envisions a two- to three-gram “starchip” micro probe, pushed by laser to a velocity of 20% of the speed of light, with a baseline mission to fly past the recently-discovered planet of the nearest star, Proxima Centauri, after a journey across interstellar space lasting 20 years.
- But with the probe moving at 60,000 km/sec, the flyby encounter at the target planet lasts a few hours.
- In the baseline plan, the information generated during the flyby is stored, and communicated back to Earth following the encounter, when the probe has returned to interstellar space.
- Power for the the communications phase is critical.

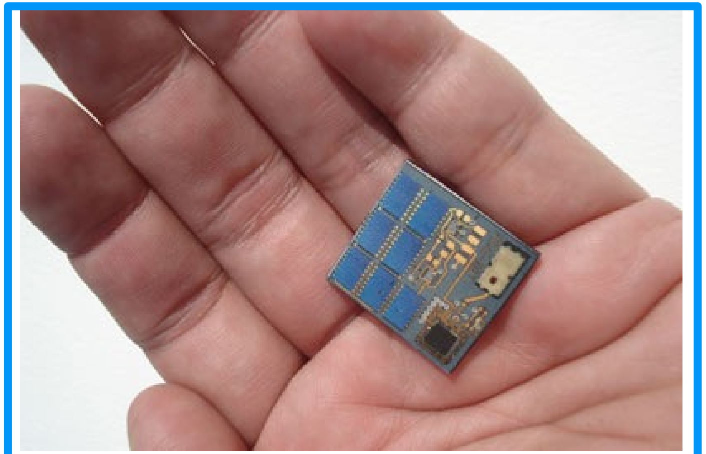
- **With current technology, no power system exists to produce the required power with mass less than one gram.**

Small interstellar probe

In order to be possible, interstellar probes must be extremely small: total mass measured in **grams** (compared to ~400 kg for the New Horizons probe).

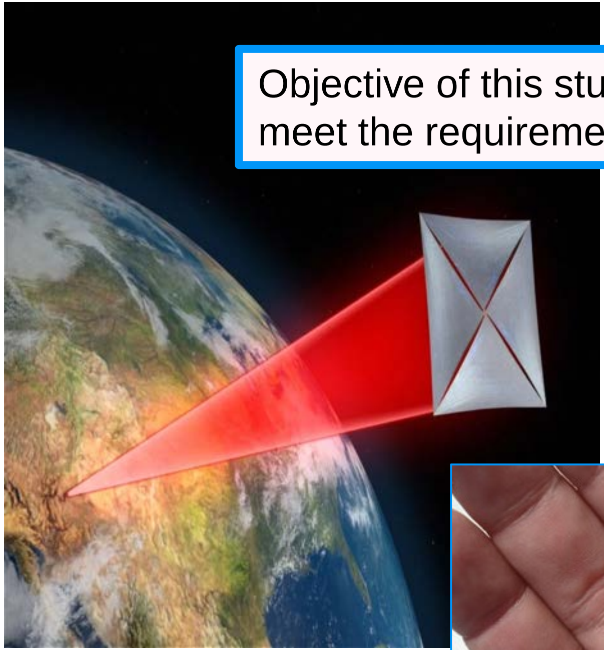


Laser-pushed lightsail micro-spacecraft concept



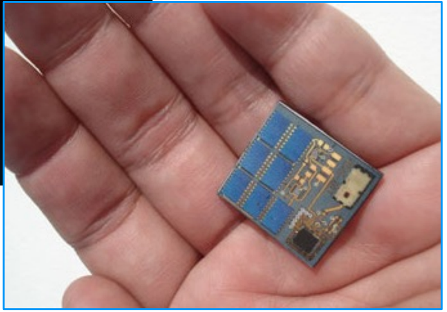
Example “chipsat” payload (image credit: Cornell University)

Objective



Objective of this study is to develop advanced power concept to meet the requirements for the mission.

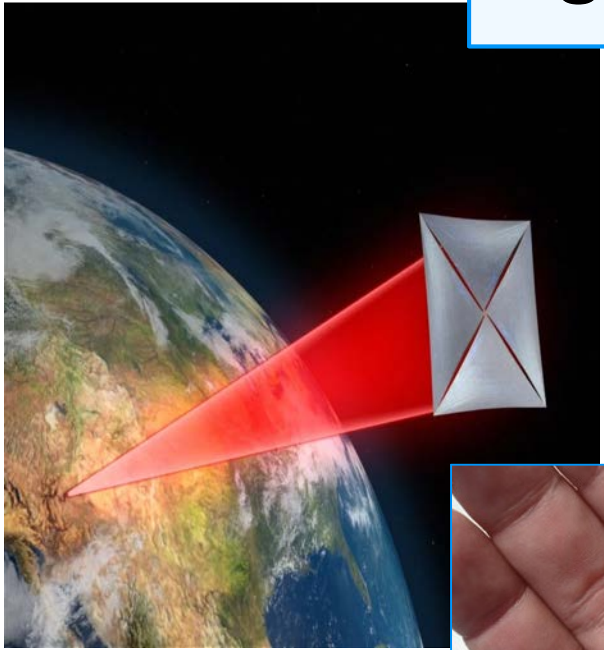
Example mission analyzed here: fly-by of planet of Proxima Centauri,



Example “chipsat” payload (image credit: Cornell University)

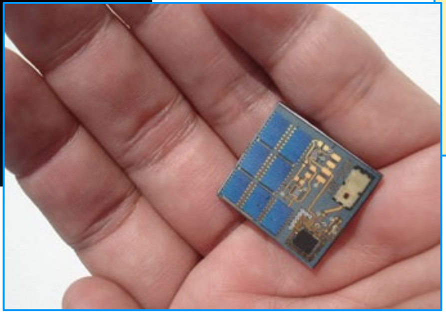
- The technologies required for mission success will need to be improved, in many cases by several orders of magnitude, over current state of the art.

Small interstellar probe



Baseline Probe Parameters:

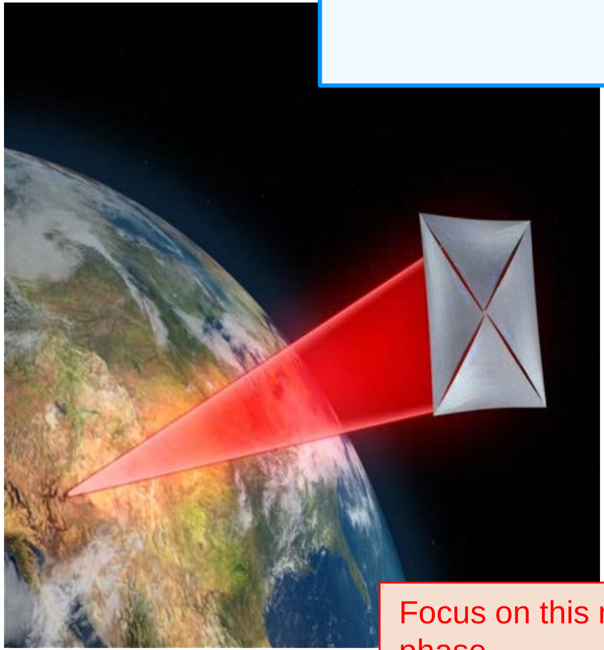
- Probe payload: **3 grams**
- Sail diameter: 4 meters
- Acceleration: 15,000 g
- Probe cruise velocity: **0.2 c**
- Cruise time to reach target: **20 years**
- Flyby:
  - time spent within 1 AU of the target: **~5000 seconds**



Example “chipsat” payload (image credit: Cornell University)

Target Star: Proxima Centauri

Power requirements:
mission phases



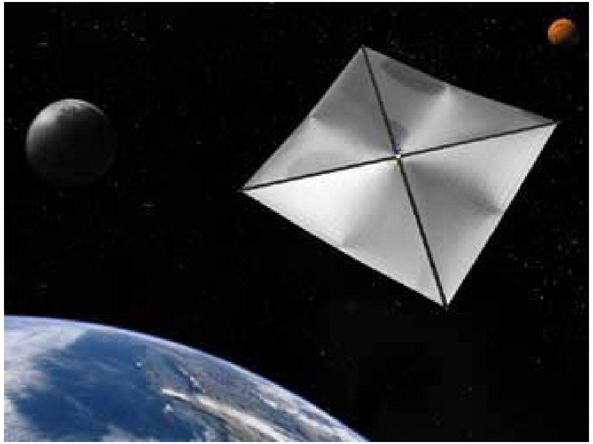
Focus on this mission phase

Power needed during four mission phases:

- *Launch*
  - ~10 minutes under laser acceleration
- *Cruise*
  - ~20 years of cruise
  - No observations; spacecraft hibernates
  - Very little power needed in cruise
- *Encounter*
  - Observations during ~one hour fly-by
  - Near target star
- *Post-encounter*
  - Return observations to Earth
  - May continue for 1 year or more after encounter
  - Communications is likely to be the highest power requirement

Small interstellar probe: Strawman power requirements

NASA Innovative Advanced Concepts



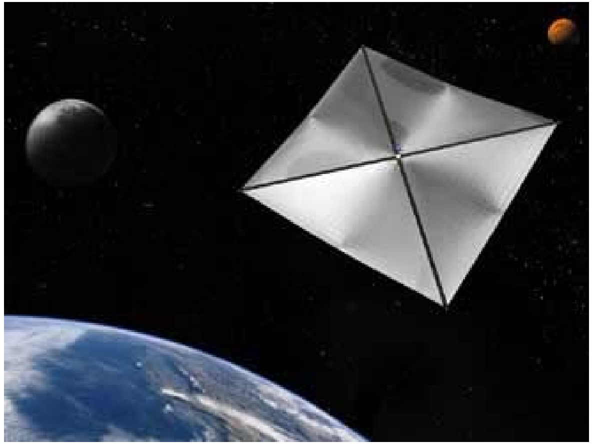
Sail approaches planet
NASA image courtesy MSFC

- Power system mass allocation **1 gram**
- Strawman power requirements: **10 mW (average) for 1 year**
  - Power required is driven by power for laser com system
    - Downlink for 1 year after encounter
    - Power requirement may change as com system design evolves
  - May require higher peak power (for brief periods)
    - This may require storage, possibly in the form of an ultracapacitor.
  - Power level can be traded off vs duration
    - Higher power for shorter duration: 100 mW for 0.1 year, 1 W for 3.6 days, etc.
    - Requirement is actually for total energy

Energy requirement: 300 kJ

This strawman power requirement does not represent requirements of a specific design; it is a design baseline for study

Power for com mission: approaches



Sail approaches planet
NASA image courtesy MSFC

Continuous power

Power is generated by on-board source which operates independent of environment

- Radioisotope thermoelectric generation (RTG)
- Radioisotope direct generation (alphavoltaic, betavoltaic)

- Generation at target

Power is generated only during encounter

- Photovoltaic power from illumination of target star
- Power from motion through magnetic field/plasma of target star

Radioisotope Power: RTG

- Analysis shows that radioisotope thermal power system scale poorly to small sizes
  - This due to the cube-square scaling factors
  - thermal losses proportional to surface area, power generation proportional to mass.
- Efficiency decreases for small systems
  - Need high temperatures for efficient radiators

Image: RTG (left) on New Horizons spacecraft
420 W (beginning of life); mass= 57 kg (11 kg of PuO_2 fuel)

- Existing RTG power systems produce about 5 mW/gram at the system level
- Decreasing mass by factor of 2 would produce the needed specific power, if specific power could be maintained at lower system size
- But it can't

RTG: disadvantages

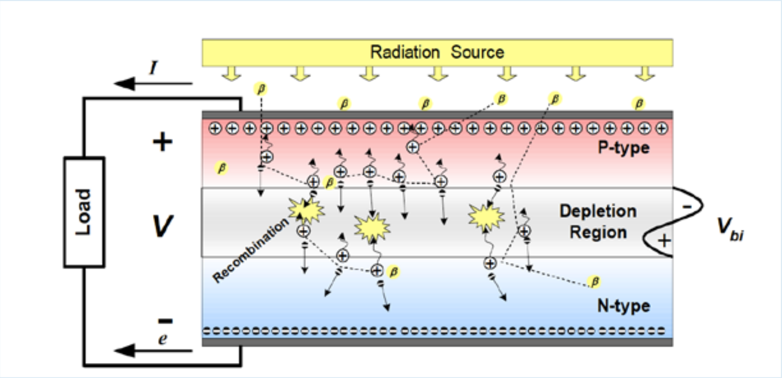
- Due to poor scaling to small sizes, a thermoelectric power system would be several orders of magnitude too heavy for such a microprobe.

Image: RTG (left) on New Horizons spacecraft
420 W (beginning of life); mass= 57 kg (11 kg of PuO_2 fuel)

Conclusion:
RTG power is not a viable power choice for this application

Radioisotope Power: betavoltaic

- An alternative conversion approach is to use direct energy conversion, rather than thermal conversion.
- In a betavoltaic cell, high-energy electrons emitted by the radioactive decay of tritium is converted to electrical power by a semiconductor device.



Isotopes: betavoltaic power

^{63}Ni beta source

- beta decay emits e- of energy up to 63 keV
  - Higher energy electrons are penetrating—needs thicker semiconductor
- beta decay power to weight ratio about 6.5 mW/gram
  - decay power is too low to meet requirement even with 100% conversion
- Half life = 100 years
  - Power at arrival = 87% of initial power
  - Not volatile (easier to plate onto devices)

Tritium (^{3}T) beta source

- Tritium beta decay emits e- of energy 19 keV
- Decay energy = 324 mW per gram
  - higher than ^{63}Ni by factor of 50
- Half life = 12.3 years
  - 20 year cruise is 1.6 half lives
    - Power at arrival = 32% of initial power (105 mW/gram)

* Note that this is the isotope alone- not electrical power

The isotope itself is not the highest mass element in the system

- Used by commercially available devices

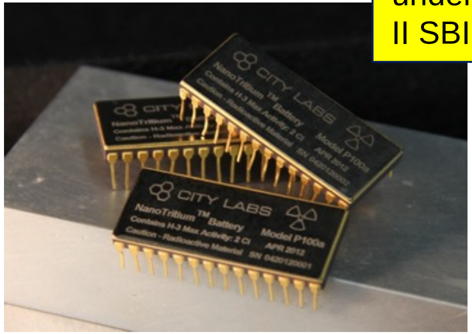
- Best isotope choice is ^{3}T
  - Other isotopes have too short half life or too low specific power at the isotope level

Other isotopes

- ^{147}Pm: high power, but 2.6 year half life- not considered
- ^{90}Sr/^{90}Y couple: high power, but MeV electrons damage semiconductor

Example of commercial Betavoltaic power source

Being developed under a NASA phase-II SBIR



Chip-sized betavoltaic power sources manufactured by City Labs

Next-generation product:
100 microwatts
20.1 grams including packaging

We want 10 milliwatts for 1 gram:
100 times more power for 20 times lower mass:
Not impossible…. But still needs work

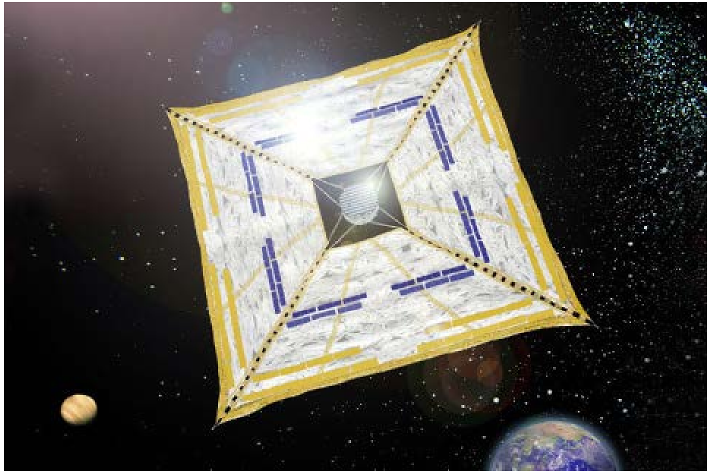
Images courtesy City Labs.
References:
https://citylabs.net/products/
https://citylabs.net/wp-content/uploads/2018/03/NanoTritium-Battery-Spec-Sheet-P200-with-application-sheet-8-29-17-REVISED.pdf

Radioisotope Power: alphavoltaic

- **Alternative radioisotope direct conversion technology is alphavoltaic, in which the energy of alpha particles from spontaneous fission are used.**
- Alpha-emitting isotopes have higher specific power than the beta sources:
    - $^{238}PuO_2$: thermal energy 390 mW/gr (half life 87.7 years)
    - $^{244}Cm_2O3$: 2270 mW/gr (half-life 17.6 years)
  - Alphavoltaic converters have been made commercially; with a 10-mW alphavoltaic battery having a mass of 30 g.
    - Needs mass reduction
- However: the high-energy alpha particles creates damage that degrades the semiconductor alphavoltaic converters
- Current semiconductor technology does not make 20-year lifetime requirement.
  - **Alphavoltaic sources may become a possible power source if new technologies solve the problem of radiation-damage limited lifetime.**

IKAROS:

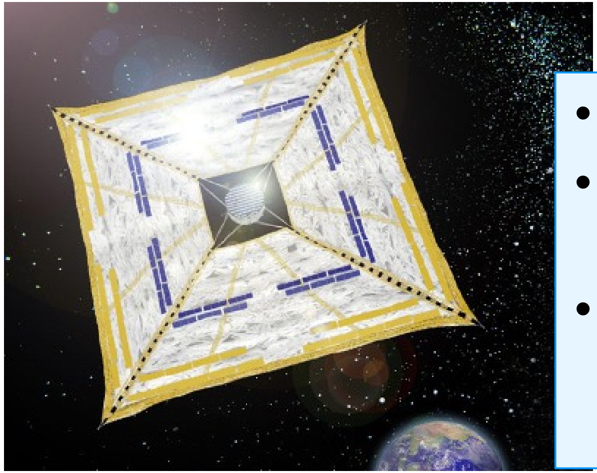
a solar sail with photovoltaic power on the sail surface



IKAROS solar sail spacecraft: artist's conception. Photovoltaic elements are blue rectangles on the sail surface

images courtesy JAXA:

Photovoltaic Power



- Spacecraft is powered by the target sun
- Probe images as it flies through target solar system, then communicates images as it leaves solar system
- Communication ends when solar power is unavailable
  - Higher power needed: communicate for ~hours, not years
  - Needs photovoltaics to operate at wide range of intensities

Current technology is far too heavy for this mission
Future technology is need to make high efficiency solar cells very thin and deposit onto flexible substrate
- not impossible… but very difficult

Would need to be high temperature tolerant!
Would need to tolerate multiple holes due to interstellar cruise

Photovoltaic power

Baseline assumption: solar array directly on sail (no added mass for array)

Current monocrystalline triple-junction solar cells achieve efficiencies well over 30%
However, to minimize mass, this approach will assume a single junction cell.

Approaches:

Thinned crystalline cell:

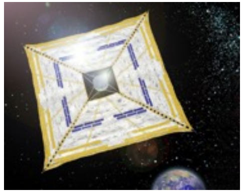
Single crystal cells currently produce the highest efficiency and lifetime in space.
To achieve the low mass required, the active cell must be removed ("peeled") from the thick growth substrate to produce a cell of micron thickness
Possible material choice: GaAs, efficiency 20%

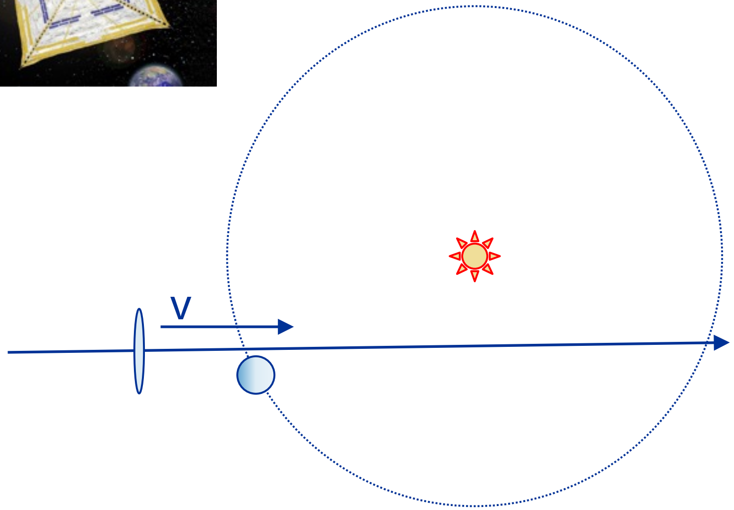
Deposited thin-film material:

Possible choices: perovskite, amorphous silicon, CdTe thin films
Perovskite solar cells are thin films that can be directly deposited in sub-micron thickness on the plastic substrate, and efficiencies of the best perovskite cells are approaching single crystal efficiencies, but as of now, lifetime is limited, and has not yet been demonstrated in space

The design exercise here will assume thin-film materials like perovskites can be deposited directly on the sail and achieve efficiency comparable to GaAs single crystal cells

How close passage to star?





- After passing the planet, the probe can continue to a closer pass to the star*
- This allows us to generate power at a higher incident power density, and thus using a smaller array. If efficiency is independent of temperature and intensity, the power generated is inversely proportional to the minimum distance.
- **But** at very high intensities, photovoltaic efficiency decreases due to resistance and temperature
- For the back of the envelope calculation here, we assume a closest pass equivalent to 0.5 AU (4 x solar intensity; roughly equivalent to Venus orbit)
- This allows us to use conventional solar technology
- However, a better solution would be to use a solar cell optimized for concentration and temperature and make a much closer pass.

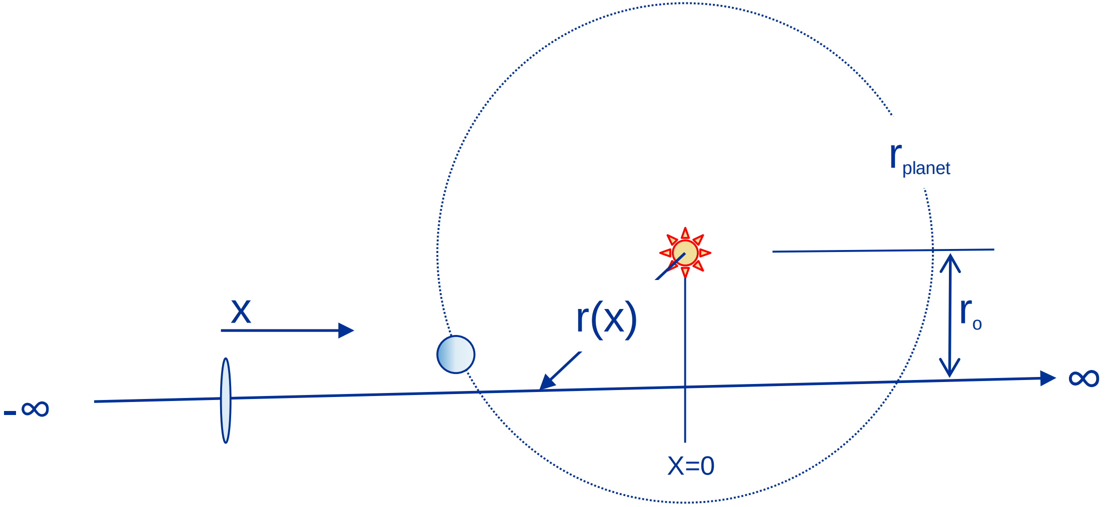
*Footnote: assuming the planet's orbital plane is not face-on to the direction of travel.

Integrate power over trajectory

- Total energy needed 300 kJ
- Assume photovoltaic output proportional to intensity
  - efficiency varies with I in the real world, so calculation is an upper bound on energy
- Integrate power over trajectory from encounter to ∞
  - We can call the trajectory a straight line, since $V_{spacecraft} >> V_e$
- $P = \eta I_o (R_o/R)^2 \qquad E = \int P dt$

- Assumption that power generated is proportional to intensity:
  - Neglects the change of photovoltaic voltage and efficiency with temperature and intensity
  - Cells more efficient at low temperatures (at farther distances from sun)
  - But voltage variation with temperature mean may not be possible to use added power

Integrate power over trajectory



Define I_o as the solar intensity at closest approach,
and P_o as power at closest approach:
$P(r) = P_o(r_o/r)^2$

Define I_o as the solar intensity at closest approach, and P_o as power at closest approach

$E = \int P dt = \int P_o(r_o/r(x))^2 dt$

Since $dt = dx/v$, $E = (P_o r_o^2/v)\int (r(x))^{-2}\, dx$

$r(x) = \mathrm{SQRT}\,(x^2+r_o^2)$ so $E = (P_o r_o^2/v)\int (x^2+r_o^2)^{-1}\, dx$

This is exactly integrable. For the total power:

$E = (P_o r_o/v)\,(\tan^{-1}[x/r_o])$ evaluated from $x/r_o = -\infty$ to ∞

$\mathbf{E = \pi(P_o r_o/v)}$

Since r_o/v is simply the the amount of time it takes to travel a distance of r_o, this is the power at closest approach times the amount of time it takes to travel π times r_o

For the case where the probe only requires power after it makes passes the planet and then begins to transmit data, if we assume the closest approach to the star is half the orbital distance of the planet ($r_o/r_{planet} = 0.5$), and the planet is passed in optimal configuration on the portion of its orbit closer to Earth, then the integral starts at $x = \sqrt{3}r_o$ and the integral is from $-\sqrt{3}r_o$ to ∞ :
$E = 5/6\pi(P_o r_o /v)$

Integrated power

- A more convenient way to express this is in terms of the time it takes the probe to travel a distance equal to the planet's orbital radius ($t = r_{planet}/v$), and the power generated at the planet's orbital radius, P_{planet}.
- Assuming that the probe's minimum approach to star is $0.5\ r_{planet}$

$$E = 5.23\ P_p t$$

Photovoltaic power

Example calculation: target is sunlike star

- assume I at planet distance = 1.36 kW/m^2
  - (i.e. one solar intensity, for R measured in AU)
- efficiency η=20%
  - About the best single-junction solar cells in use today
  - Power at planetary distance P_p = 270 W/m^2
- V = 1/2500 AU/s
- t = 2500 sec
- E = 5.23 $P_p t$ = 3.5 MJ/m^2
  - The 300 kJ requirement for communications translates to

0.085 meter^2 of solar array

Photovoltaic power

Example calculation: target Proxima Centauri

- assume Io = 2.3 W/m^2 at 1 AU
  - Based on bolometric luminosity 0.0017 $L_\odot$
  - Planet is actually 0.048 AU, so I_p is 1 kW/m^2
  - Not too different from Earth (no surprise, since this defines the habitable zone)
- efficiency η=15%
  - Assumes solar cell can be optimized for the red spectrum
  - assumes reduced efficiency due to narrower bandgap material
  - Power at planetary distance (P_p) is 150 W/m^2
- V = 1/2500 AU/s, R_m = 0.048 AU
  - T = 120 seconds
- $E = 5.23\, P_p t = 5.23\,(150)(120) = 95$ kJ/m^2
  - The 300 kJ requirement for communications requires 3.2 meter^2 of solar array

Fundamental problem is the very short residence time in the system. To generate 300 kJ in 2 minutes, power system must produce **2.5 kW**

Radiation

- Probe will accumulate radiation dose during 20-year cruise
- Three sources of radiation
  - Cosmic rays
  - Radiation due to probe's motion through ambient interstellar medium
    - Ambient medium is primarily neutral and ionized hydrogen
    - Radiation is thus protons and electrons
- Radiation due to probe's motion is the dominant flux
- Energy:
  - **10 keV electrons**
  - **19 MeV protons**
  - **25 MeV helium**
- Flux depends on which direction you go
  - Proxima Centauri mission: outside the local cloud
  - Density is ~0.001 to 0.05 H per cm^3.
  - At 0.05/cm^3 density, **20-year total fluence ~ $10^{17}/cm^3$**

Photovoltaic power:
radiation damage assumptions

- **10 keV electrons**
- **19 MeV protons**

At these energies, most of the electrons stop in ~1μ of material, while protons and helium ions will pass directly through both the cover and the active material.

Design approach:

1. use extremely thin active layers to minimize radiation degradation.
   (this will have the advantage of also decreasing mass).
2. use a thin dielectric film to stop the 10 keV electrons
   penetration depth ~1 μ;
   needs optimization of mass versus degradation

Intersection with interstellar dust will also create holes in the photovoltaic film. It is assumed that this can be made negligible by orienting the sail edgewise to the incident flux.

- These assumptions must be verified if the photovoltaic option is selected

Photovoltaic mass

Device Total thickness: 2.5 microns
1 micron transparent coating, density 2.7
0.5 micrometer active cell density 5.3
0.5 micrometer contact metallization, density 2.7

Absorption coefficient of PbI3 perovskite is >2 10^4 cm^{-1} in the range of 300-800 nm, and so a 0.5μ would could absorb >63% of the light of a full thickness cell. Incorporating rear surface reflection, 20% efficiency should be possible. These are optimistic assumptions for a 20% efficient cell, but not impossible

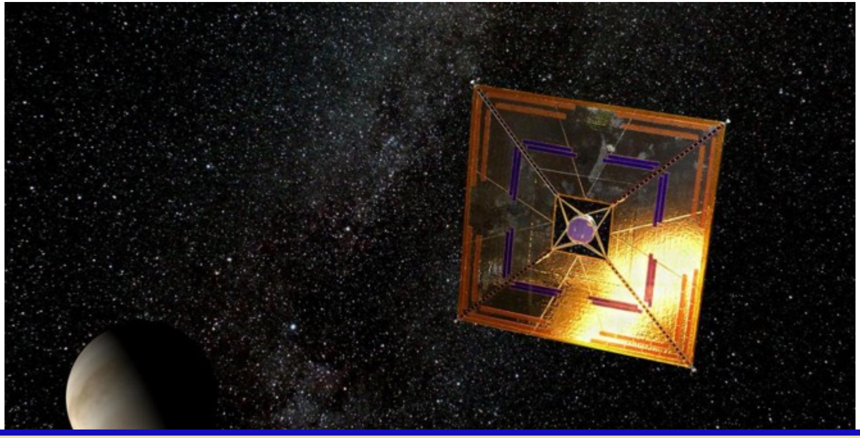
4.6 grams per square meter has been demonstrated for perovskite cels, but not with the required efficiency

Area weight = 6.7 grams/m^2
Mass of 0.085 meter solar array = **0.6 grams**
Mass of 3.2 meter solar array = **21 grams**

Array mass is the right order of magnitude, but too high for the proxima planet mission

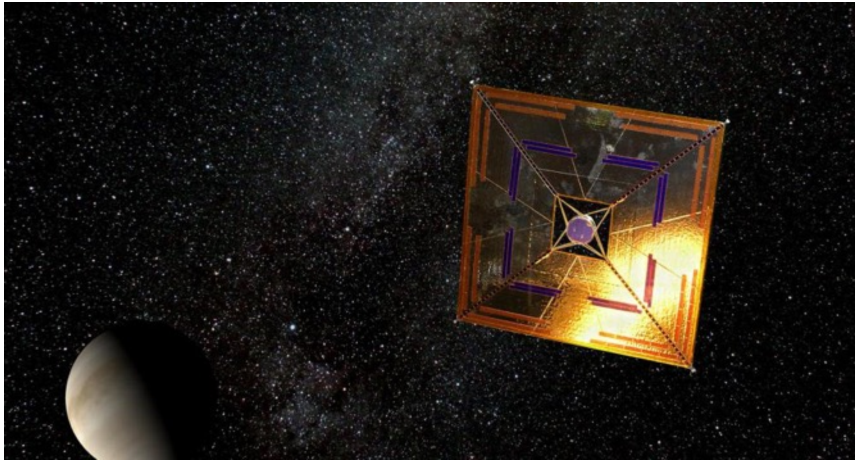
Assumptions are *very* optimistic:

- Does not include wires
- Does not include power management (assumes same efficiency at all distances)
- Does not include any allocation for efficiency loss due to degradation during cruise



- Power source for the interstellar micro-probe is a difficult problem
- *None of the analyzed power sources meets all the requirements off the shelf*
- Assumptions here are optimistic, and look at only primary power generation (does not include wiring, power conditioning, etc)

- **Radioisotope Thermoelectric Generator**: does not scale to low power
- **Betavoltaic power:** possible choice
  - Needs development to reduce mass
- **Alphavoltaic power**: degrades due to alpha radiation
- **Photovoltaic power:** looks promising if mass is reduced
  - Does not work for Proxima planet
    - Assumptions were optimistic: Needs low mass & radiation tolerance



- But… our probe itself represents *plenty* of kinetic energy
  - This is the energy we put into the probe by launching it
- $E = \frac{1}{2} m V^2$… and we're moving at 1/5 the speed of light*
- If we could tap our own energy of motion, the energy problem is solved

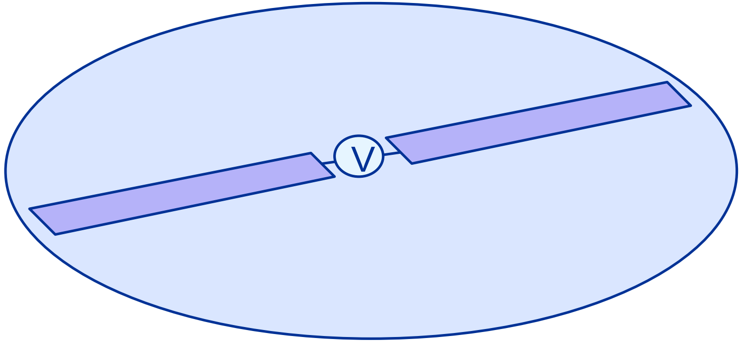
- Probe isn't moving in its own reference frame
  - We can only access this energy if we're moving **with respect** to something.
  - We're moving with respect to the interplanetary medium (of the system we're entering), and with respect to the interstellar medium (when travelling)
- In our reference frame: we want to use the energy of the plasma moving past us

*Footnote: V=0.2c (6E7 m/s), At 0.2c we are sub-relativistic, so the non-relativistic energy formula is reasonable.

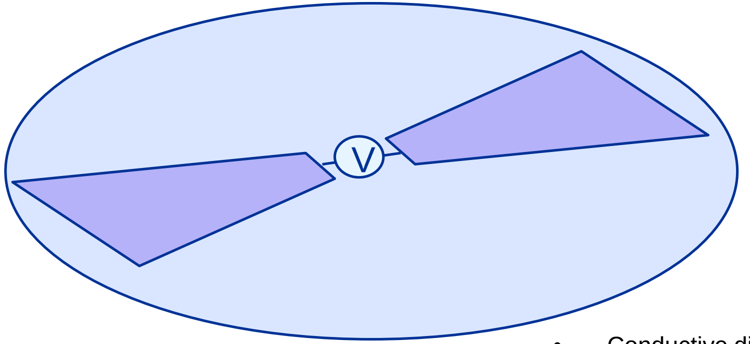
Advanced power concept

- Generate power from the motion of the spacecraft through the target star's environment
- Approach 1: Use the magnetic field of the target star,
- Power can be generated by the vxB potential of spacecraft movement in the star's magnetic field
  - Similar to "electrodynamic tether"
  - Current loop must be grounded via contact to the ambient plasma

Conductive stripe on sail



- Conductive dipole on sail: rectangular strip



- Conductive dipole on sail: pie-wedge strip (“bow-tie dipole”)

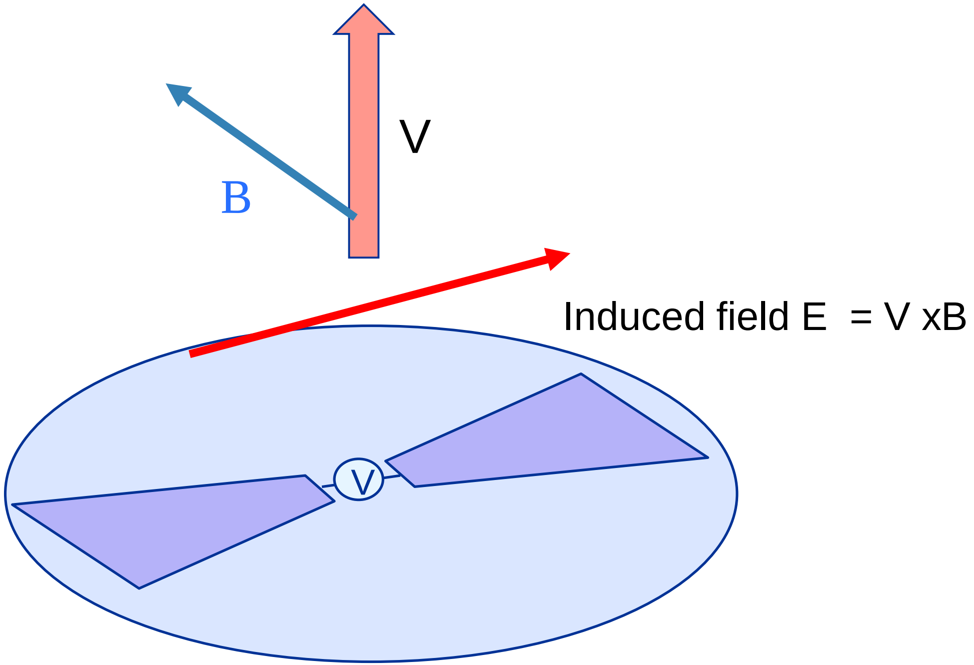
Generates power from the motion of the spacecraft through the target star’s environment

Use the magnetic field of the target star,

Power can be generated by the vxB potential of spacecraft movement in the star’s magnetic field

- Similar to “electrodynamic tether”
- Current loop must be closed

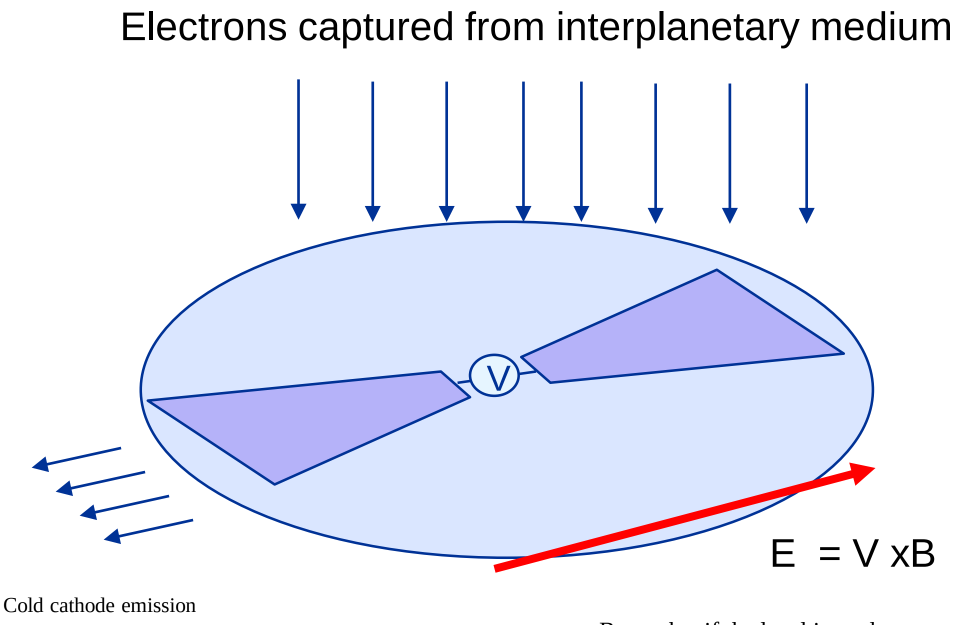
Induced field



For the solar magnetic field (measured at 1AU during a quiet-sun period), this comes to about 250 volts across the sail

Current closure

For all energy generation, the current must flow in a complete circuit, (Kirchoff's current law).
We can close the current loop through the ambient plasma



But– what if the local interplanetary medium isn't ionized?
--doesn't matter. At 0.2C, passage of neutral hydrogen through the sail will strip electrons

Current closure

Electrons captured from interplanetary medium

Interplanetary medium is the solar wind

- Consists of equal numbers of both protons and electrons
  - Protons pass right through thin sail
  - Minor amount of higher mass particles (D, He) can be neglected
  - Electrons stopped in sail

Density of solar wind at Earth's distance from the sun = 4/cm^3

  - varies with solar activity
  - Similar or higher at Proxima Centauri
  - At V=0.2c (6E7 m/s) this is 2.4E10/cm^2 per second

- Charge = 1.6E-19C/electron, closure current is 0.04 milliamps/m^2

Magnetic field of Proxima Centauri: good

We're in luck! Magnetic fields of M-dwarf stars (like Proxima Centauri) are high.

Estimated field at distance of Proxima planet is 0.3 Gauss to 1.2 Gauss (lowest value, 30 microTesla, is comparable to Earth's field)

(Assumes dipole field)

E = v x B

- In SI units: v in m/s, B in T

E = 0.2 * 3E8m/s * 5E-5 T = 3000 V/m

At current of 0.04 milliamps/m^2

P = IV = 4E-5A/m^2*3E3 V/m = 0.12W/m^3

References:

- "Magnetic fields in M dwarfs from the CARMENES survey", D. Shulyak, et al.
- "Magnetic cycles in a dynamo simulation of fully convective M-star Proxima Centauri," Rakesh K. Yadav, Ulrich R. Christensen, Scott J. Wolk, and Katja Poppenhaeger

Magnetic energy harvesting at Proxima Centauri: bad

But…

Proxima Centauri is so dim that the planet is very close to the star.

Earth solar intensity at 0.04 AU; “goldilocks zone” planet at ~ 0.05 AU

→ At 0.2 c, our probe passes through habitable zone in about **2 minutes!**

- Not possible to generate power fast enough during the short time probe is within the magnetic field

Power from ambient plasma

- Power can be generated from the impingement of the ambient plasma on the spacecraft
  - Environment at encounter is primarily protons and electrons (ambipolar plasma), plus neutrals
  - Incident particle flux is thus protons and electrons
  - Spacecraft motion produces:
    - E (electron) = 10 keV
      E (proton) = 19 MeV
- Easy to capture electrons
- Harder to capture protons (pass through thin sail)
- Issue: power is generated at characteristic voltages of 10 keV to 19 MeV!
  - Can it be transformed to lower voltage without excessive mass?
  - Or, can power be used at this voltage?

Incident particle flux

- Particle energy at 20% of c:
  - **10 keV electrons**
  - **19 MeV protons**
  - **76 MeV Helium** (about 4% of the flux)
- Current at 20% of c:
  - **0.04 milliamps/m^2** (both electrons and protons)*
- Total energy available :
  - **0.4 W/m^2 electrons**
  - **760 W/m^2 protons**
  - **490 W/m^2 He**

*For now we are assuming that the Proxima Centauri plasma environment is similar to the Sun's.

Local interstellar medium

We also might get power during cruise from probe's motion through ambient interstellar medium

- Ambient medium is primarily neutral and ionized hydrogen
  - A few percent helium

- The sun is embedded in the "local cloud", with a density of 0.1-0.2 partially-ionized hydrogen atoms per cubic centimeter.
- α Centauri is located outside the local cloud.
- Surrounding the local cloud is the local bubble, about 300 light years in diameter, with density ~0.001-0.05 hydrogen ions per cubic centimeter.

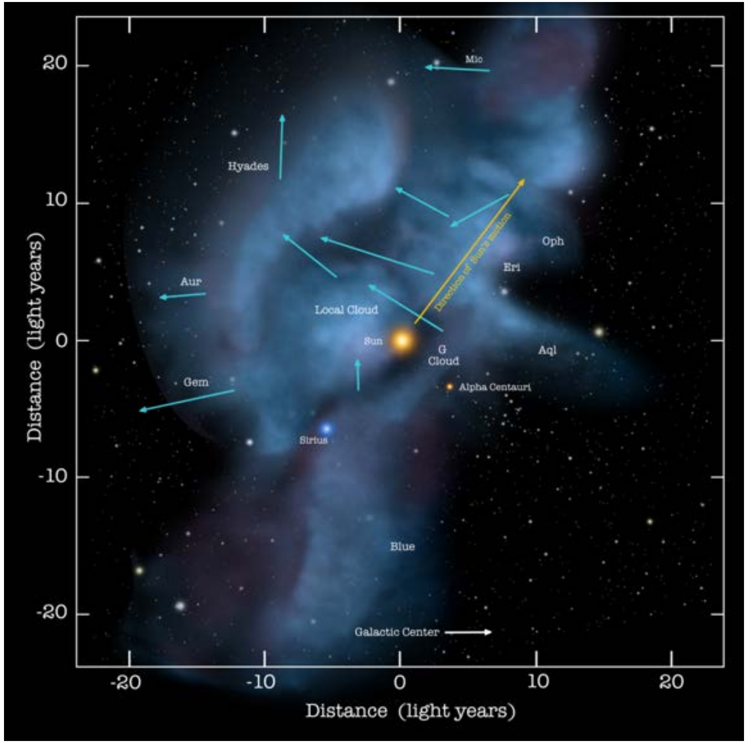
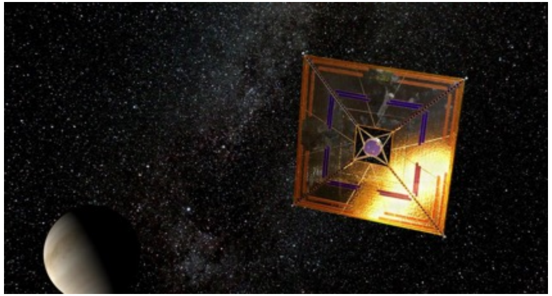


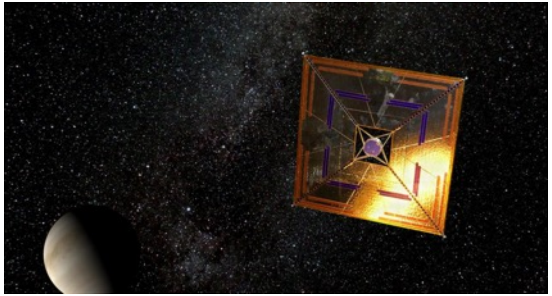
Image from NASA Goddard: https://svs.gsfc.nasa.gov/10906

Geoffrey A. Landis



Some conclusions

- The ultra-miniature fly-by spacecraft requires a power system orders of magnitude and lighter smaller than anything previously made
  - This is not a solved problem
  - but several plausible approaches exist



Some conclusions

- Harvesting energy during passage through Proxima Centauri system is particularly difficult:
  - since it is such a dim star, we pass through the system in minutes, making it hard to generate power fast enough
  - The best approach might be to pick a different (more sunlike) target star
- Analysis continues